NITROGEN BUFFER GAS EXPERIMENTS IN MERCURY TRAPPED ION FREQUENCY STANDARDS

R.L. Tjoelker, S. Chung, W. Diener, A. Kirk, L. Maleki, J.D. Prestage, B. Young
Jet Propulsion Laboratory, Pasadena, CA

Abstract

Practical, continuous operating mercury trapped ion frequency standards have traditionally used a helium buffer gas to increase loading efficiency and cool ions to near room temperature. The fractional frequency shift of the 40,507,347.9968x Hz clock transition due to collisions with helium is measured to be $(df/dP_{He})(1/f) = +1.2\times10^{-10}$/Pa . The use of a nitrogen buffer gas is considered for low power and mass applications where unattended operational life must be greater than 10 years. The nitrogen pressure shift is measured to be $(df/dP_{N2})(1/f) = -8.7\times10^{-9}$/Pa. Nitrogen would allow long operation with a only small ion pump but require increased pressure regulation to achieve the ultra-high stability obtained using helium in multipole Hg+ standards.

Introduction

Mercury linear ion trap frequency standards (LITS) have been in continuous operation in the NASA Deep Space Network (DSN) since 1996 [1]. Stability floors in the 10^{-16} range are reached with the LITS and a stability of 1×10^{-16} is expected with the recent demonstration of a multipole extended Linear Ion Trap (LITE) [2,3]. The practical features of the LITS and excellent stability performance makes this an attractive technology for a number of spaceflight applications. These include applications such as on a GPS-Navstar satellite which have extremely demanding requirements for long operational life and reliability.

Standards with Helium Buffer Gas

Buffer gas based ^{199}Hg+ ion standards contain no lasers, cryogenics, or cavities and provide a significant advantage for demanding operational environments where high frequency stability is required. Atomic state preparation is accomplished via optical pumping with an RF discharge lamp, and the ions are loaded and held near room temperature using a helium buffer gas. Helium has typically been the buffer gas of choice but constrains vacuum pump selection and operational lifetime.

Linear Ion Trap Standard (LITS)

The traditional LITS standards are based on a four rod configuration which generates a two dimensional quadrupole for radial confinement. Axial confinement is with dc fields. The largest perturbations to the clock transition are the dc Zeeman (magnetic) shift, second order Doppler shift, and collision pressure shift [4]. The second order Doppler shift is the most challenging offset to control in the long term as instabilities in the confined ion number lead to fluctuations in the average ion temperature resulting from rf heating.

Approximately 10^{-5} Torr of helium is used to increase ion loading efficiency and limit the effects of rf heating from the trapping fields. This is dramatically evident in Figures 1a and 1b. Figure 1a shows the observed shift in the 40,507,347.9968x Hz clock transition as a function of changes in the helium buffer gas pressure. This characteristic shift has been observed previously in both quadupole linear [4] and spherical [5] ion traps. At higher pressures, the nearly linear slope is interpreted to be the helium pressure shift of the ^{199}Hg+ (F=0,m=0 to F=1,m=0) ground state transition. At low pressures the large negative shift is interpreted to be Doppler pulling resulting from an increase in the average temperature of the ion cloud. Figure 1b shows the effect on loading efficiency. The signal size represents the amplitude of the 40.5 GHz transition which is proportional to the total number of ions stored. At low buffer gas pressure we trap a smaller ion cloud, with a higher equilibrium temperature.

Due to the second order Doppler shift and to pressure shift a tradeoff exists between vacuum pump and buffer gas selection, pump life, and achievable frequency stability performance. The present DSN standards operate with mechanical turbo-molecular and backing pumps to provide a relatively constant "ageless" pumping speed over their operational life. Unattended operation is presently limited to 1-2 years by needed mechanical pump maintenance.

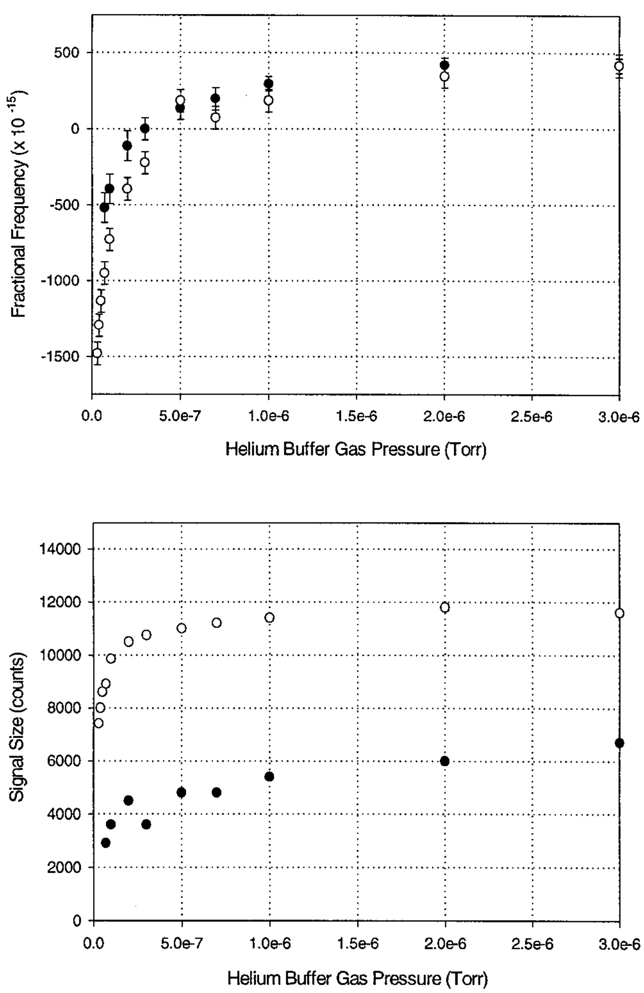

Figure 1: (a) Helium collision shift in the LITS four rod quadrupole trap with two different size ion clouds. Note the large second order Doppler shift that results from low buffer gas pressures. (b) The corresponding maximum signal size proportional to to trapped ion number.

Multipole Ion Trap-LITE

Mulitpole ion trap geometries have recently been proposed [2] and demonstrated [3] that greatly reduce the second order Doppler shift which previously resulted from variations in the size of the ion cloud. In the multipole LITE configuration, ions are loaded in a traditional "open" quadrupole linear trap which provides needed optical access for state preparation and detection. Ions are then moved into a "closed" multipole trap for microwave interrogation. The multipole trap effectively turns off the rf heating by replacing the tight confining quadrupole with a large, loosely confined well. Recent measurements with a 12 pole trap show are reduction of the second order Doppler shift due to the confining rf fields by at least a factor of 20. This should directly enable a large improvement in long term stability.

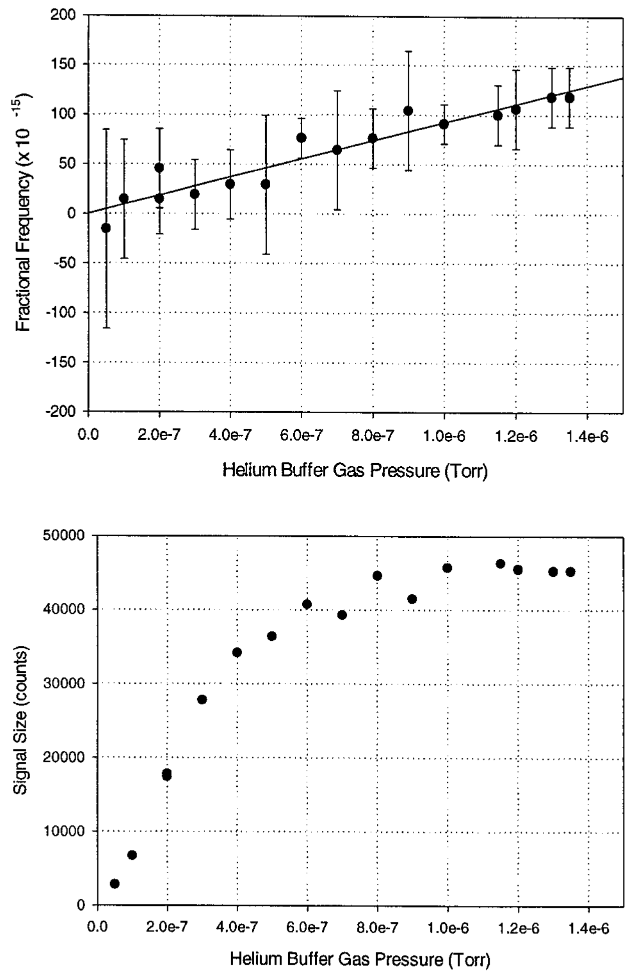

Figure 2: (a) Helium collision shift of the clock transition as a function of indicated helium buffer gas pressure in the 12 rod multipole LITE standard. In contrast to Figure 1a there is little rf heating evident at low pressure. (b) The corresponding signal size proportional to the trapped ion number.

This dramatic Doppler shift reduction is also evident in the buffer gas pressure sensitivity measurement. Figure 2a shows helium pressure shift measurements in the multipole ion trap. The ion heating at low buffer pressure seen in Figure 1 is not observed on this scale allowing for an unambiguous measurement of the pressure shift. Figure 2b shows the signal amplitude as a function of buffer gas. The fractional frequency shift of the 40.5 GHz clock transition is $(df/dP_{He})(1/f) = 1.7\times10^{-8}$/ Torr or 1.2×10^{-10}/Pa. Although the rf heating mechanism is "turned off" the reduced ion loading efficiency at low pressure is evident. Because of the need to transfer ions between the quadrupole and the multipole, the loading efficiency in this context also includes the transfer efficiency between the loading and interrogation traps.

Vacuum Pumps and Buffer Gas Leaks

The operational buffer gas pressure is the equilibrium pressure between the input rate and the pumping speed. For typical clock operation we introduce helium through a heated quartz leak consisting of a thin quartz tube wrapped with ni-chrome wire. The leak is pressurized to 30 psi and heated sufficiently hot to diffuse enough helium to produce the indicated pressure. For clock operation the leak rate is stabilized around $2x10^{-6}$ Torr as measured by a Granville Phillips series 360 ion gauge controller. When correcting for the ion gauge sensitivity the actual helium pressure is 5.56 times higher.

The effective pumping speed depends on the pump and vacuum system throughput. We have favored using mechanical pumps for applications where long term stability is a primary concern. We have operated with ion and getter pumps though the ion pump life is limited when exposed to such a large amount of helium for extended periods of time.

Buffer gas can also be introduced through a mechanical or pinched capillary leak as long as the gas is free from contamination. For introducing gases such as nitrogen we have used both precision sapphire leak valves and pinched capillary leaks. Both require no power to operate, though mechanical leaks need to be in a stable thermal environment. Presently we have no active feedback to further stabilize the buffer gas pressure. Therefore the stability of the pumping speed together with the sensitivity of the collision shift determine the long term stability floor.

Nitrogen Pressure Shifts in $^{199}Hg+$

Nitrogen pressure shifts have been measured in both the LITS and the multipole LITE frequency standards. As with helium, the LITS shows a large second order Doppler shift for low buffer gas pressures. Figure 3a shows the fractional frequency shift of the clock transition when nitrogen is introduced into the multipole LITE standard through a Sapphire variable leak.

The pressure is monitored with a Granville Phillips 360 series ion gauge and controller. We have performed no additional calibration of the gauge or controller beyond the factory calibration. The sensitivity correction factor in the controller manual for nitrogen is 1.0. The fractional frequency shift of the 40.5 GHz clock transition is $(df/dP_{N2})(1/f) = -1.2x10^{-6}/$ Torr or $-8.7x10^{-9}/Pa$. This is about 70 times more sensitive than the shift observed with helium and opposite in direction.

Vacuum Pumps and Stability Implications

Nitrogen measurements have been performed using both mechanical pumps and ion pumps alone. The much larger pressure shift and sensitivity places a constraint on the required stability of the buffer gas leak rate and the vacuum pump speed. For example, to reach $2x10^{-16}$ frequency stability the helium pressure must be stable to 10^{-8} Torr over the averaging interval. To break 10^{-15} stability with

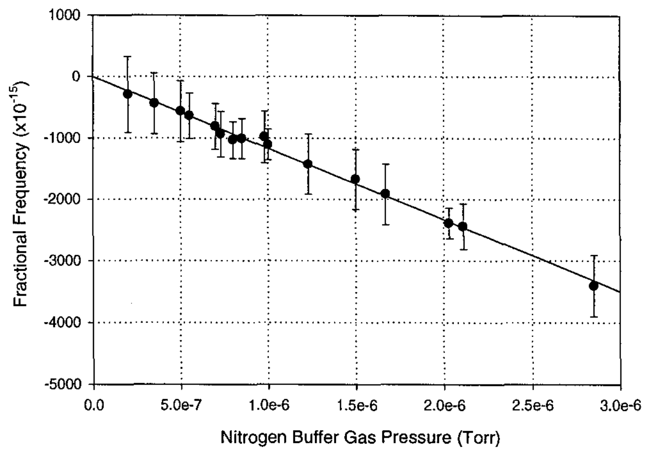

Figure 3: The collisional shift for Nitrogen buffer gas as measured in the 12 rod multipole LITE standard. A large, negative collision shift is observed free of Doppler effects.

Nitrogen requires the nitrogen pressure to be stable to 10^{-9} Torr over the averaging interval.

In a multipole trap where the second order Doppler shift is significantly reduced, the buffer gas shift and pumping speed stability become the leading limitation to further stability. For ground based applications where stability is the foremost goal it may be advantageous to mix helium and nitrogen buffer gas at an optimum ratio to reduce sensitivity to total pressure variations. Operation with mixed helium and nitrogen has been performed without apparent degradation in signal to noise as observed with helium alone.

For small practical applications, e.g. onboard a Navstar GPS satellite where longevity, robustness and good stability is required, nitrogen buffer gas provides an alternative to helium. Nitrogen appears to be an effective buffer gas with $^{199}Hg+$ even at pressures in the mid 10^{-7} Torr range. At this pressure, many years of operation should be possible with only a small ion pump. The efficacy of other gases that can be gettered by an ion pump are also under study. Candidate gases include CO, CO2, O2, H2. Neon and argon are also under evaluation for ultra-stable ground based operation.

Conclusions

Nitrogen can be used as an alternative buffer gas under conditions where many years of operational life are required. Although the nitrogen pressure shift is larger than with helium, long frequency standard operation can be achieved with only a small ion pump. For ultra-stable ground operation, an optimized mixture of helium and nitrogen could eliminate any net shift as the total pressure varies. Other buffer gas candidates are under evaluation that may allow even higher stability or longer operational life

Acknowledgments

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the U.S. National Aeronautics and Space Administration.

References

[1] R.L. Tjoelker, C. Bricker, W. Diener, R.L. Hamell, A. Kirk, P. Kuhnle, L. Maleki, J.D. Prestage, D. Santiago, D. Seidel, D.A. Stowers, RL. Sydnor, T. Tucker, "A Mercury Ion Frequency Standard Engineering Prototype for the NASA Deep Space Network", Proc. Of the 50th Annual Symp. on Frequency Control, Honolulu, Hawaii June 5-7, 1996.

[2] J.D. Prestage, R.L. Tjoelker, L. Maleki, "Higher Pole Linear Traps For Atomic Clock Applications"; 13th European Frequency and Time Forum and the 1999 Ieee International Frequency Control Symposium Besancon, France, April 13-16, 1999.

[3] R.L.Tjoelker, J.D. Prestage, L. Maleki, "Improved Timekeeping Using Advanced Trapped Ion Clocks", PTTI, Dana Point, California, December 1999. See also J.D. Prestage, R.L. Tjoelker, L. Maleki, "Mercury Ion Atomic Clock Based on a 12-Pole Linear Trap", these proceedings.

[4] R.L. Tjoelker, J.D. Prestage, G.J. Dick, L. Maleki, "Long Term Stability of Hg+ Trappped Ion Frequency Standards", Proc. Of the 47th Annujal Symp. on Frequency Control, pp. 132-138, (1993).

[5] L.S. Cutler, R.P. Giffard, and M.D. McGuire, "Thermalization of 199Hg Ion Macromotion by a Light Background Gas in an RF Quadrupole Trap", Applied Physics B36, pp. 137-142 (1985).